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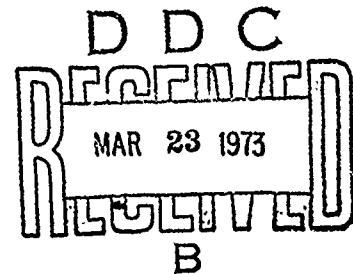
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EFFECT OF CRYOGENIC TEMPERATURES ON THE PERFORMANCE OF SELECTED EXPLOSIVES

Prepared for
NAVAL EXPLOSIVE ORDNANCE DISPOSAL FACILITY

by
B. D. Trott
of
BATTELLE
Columbus Laboratories

August 1972



**NAVAL EXPLOSIVE ORDNANCE DISPOSAL FACILITY
INDIAN HEAD, MARYLAND 20640**

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**NAVAL EXPLOSIVE ORDNANCE DISPOSAL FACILITY
INDIAN HEAD, MARYLAND 20640**

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ABSTRACT

The effect of liquid nitrogen temperature on the performance of eleven selected detonating and deflagrating compositions was studied experimentally. The detonating explosives included two military explosives, medium velocity dynamite and composition C-4, and five commercially available compositions. They included two 60 percent strength dynamites, 60 percent strength nitrostarch, ammonium nitrate/fuel oil, and Red Dot smokeless powder. The smokeless powder is included with the detonating compositions because true detonation waves were found to develop in pipe-confined charges of this powder. The deflagrating mixtures studied included both homemade and commercial black powder, and two potassium chlorate mixtures, one with powdered sugar and one with Vaseline.

Measurements of the reaction velocity were made at both room and liquid nitrogen temperature. Generally there was little change in reaction velocity between these two temperatures.

For the detonating mixtures, the critical charge diameter for sustained detonation and impact initiation sensitivity were determined at both room and liquid nitrogen temperature. The critical charge diameter increases at liquid nitrogen temperature were small for the military explosives and relatively large for the commercial explosives. The impact sensitivity decreased at liquid nitrogen temperature for all the explosives, although they remained with a range (< 31 kilobars) which could be expected to be cap sensitive at liquid nitrogen temperature. None of the detonating explosives could be cap-initiated at liquid nitrogen temperature however. The principal reason for this appeared to be a reduction in the output power of the commercial and military detonating caps used, as evidenced by their effect on lead witness plates.

The deflagrating mixtures were initiated in pipe bombs at both room temperature and liquid nitrogen temperature. The potassium chlorate-Vaseline mixture was found to be essentially unreactive in these tests although it is purported to be a strong deflagrating mixture. Of the remaining mixtures, only the commercial black powder was found to react with appreciably less damaging results at liquid nitrogen temperature than at room temperature.

FOREWORD AND ACKNOWLEDGMENTS

This report comprises the final report on Contract Number N00174-72-C-0214. The work was conducted during the period February, 1972, through July, 1972. Mr. Michael Shapiro of the Naval Explosive Ordnance Disposal Facility served as Technical Monitor for the program. The able help of William F. Schola and Sheryll C. Green in the preparation and conduct of the experiments is gratefully acknowledged.

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EFFECT OF CRYOGENIC TEMPERATURES
ON THE PERFORMANCE OF SELECTED EXPLOSIVES

by

B. D. Trott

INTRODUCTION AND SUMMARY

Current theories of the initiation of detonation suggest that the initiation of all detonations is primarily thermal in character, independent of the actual means employed. When explosives or deflagrating mixtures are ignited with a flame-producing device such as a squib, the initiation is clearly thermal. When initiation occurs by high-pressure impact, however, the thermal nature of the event is not so clear cut. Adiabatic heating of most solid explosives due to the initiating shock compression is insufficient to raise the temperature of the explosive enough to produce the observed rapid reaction rates. To explain these phenomenon, initiation is theorized to occur at hot spots. The mechanisms for formation of hot spots depend on the occurrence of localized heating above the average value due to the presence of an inhomogeneity in the solid. The thermal nature of the initiation mechanisms suggests that a significant reduction in the shock sensitivity of explosives may occur if their initial temperature is lowered to liquid nitrogen temperature.

The purpose of this study was to determine the extent of this reduction for a total of eleven explosive mixtures. Three basic tests were used at both room temperature and near liquid nitrogen temperature to determine the variation in properties between these two temperatures on the formulations to which these tests are applicable. Initially, simple detonation or deflagration ignition tests were performed on all formulations at

both room and liquid nitrogen temperature using an electrical resistance probe to measure reaction velocity. Based upon these results those formulations which were found to develop detonations were tested for shock sensitivity using the NOL large-scale gap test at both room temperature and liquid nitrogen temperature. The third test was a measure of the critical charge diameter required to produce a sustained detonation in these formulations at both room temperature and liquid nitrogen temperature.

For the detonating compositions studied, all were found to be nondetonable at liquid nitrogen temperature by a Number 8 commercial blasting cap when the blasting cap was also at liquid nitrogen temperature. Separate tests of blasting cap output at room temperature compared to liquid nitrogen temperature through the use of lead witness plates showed that the blasting cap output was appreciably reduced at liquid nitrogen temperature. When other means of initiation at liquid nitrogen temperature were employed, several of the detonating compositions were found to detonate at liquid nitrogen temperature with unchanged detonation velocity within the ~ 5 percent accuracy of the experimental determination. The numerical results of these measurements are given in Table 1.

The large-scale gap test results showed that all detonating compositions studied remained detonable at liquid nitrogen temperature with decreased sensitivity to shock initiation. The decreases in impact sensitivity at liquid nitrogen temperature, however, were not large. All of the commercial detonating compositions studied were found to detonate at impact pressures equal to or less than the room temperature sensitivity

of the military explosives studied. The military explosives also suffered decreases in impact sensitivity; however the pressure required to initiate detonation still remained below 31 kilobars at liquid nitrogen temperature. The critical charge diameter required for sustained detonation did, however, increase greatly at liquid nitrogen temperature for the commercial explosives. Only in the case of 60 percent special gelatin dynamite was the critical diameter small enough to sustain detonation in a single stick. The military explosives showed either no change or very small increases in critical diameter for sustained detonation at liquid nitrogen temperature over the room temperature values. The numerical results of these measurements are given in Table 2.

For the detonating explosives studied these results show that, although there may be difficulties encountered with initiation of the explosives at liquid nitrogen temperature, once a detonation is initiated in a reasonable size charge, it would be expected to propagate with undiminished destructive power. The tests conducted showed no tendency for increased sensitivity of any of the formulations studied. However, the formulations studied did not include any of the straight dynamite compositions containing nitroglycerin merely absorbed in an absorbent medium. These straight dynamite formulations could be expected to go through a temperature range of instability near the freezing point of nitroglycerin, especially on thawing.

The deflagrating mixtures studied were fired in nominal 1-1/2-inch-diameter by 12-inch capped pipe "bombs". Both detonator boosters and electric squibs for initiation were evaluated at room temperature. The squibs were found to be more effective and hence only squibs were used at liquid nitrogen temperature. All of the mixtures

which reacted completely at room temperature also reacted completely at liquid nitrogen temperature. Only the 3FA black powder was found to react with appreciably less damaging results at liquid nitrogen temperature than at room temperature. The results of these measurements are given in Table 3.

It is recommended that further work be conducted to determine if any available detonator/explosive combinations will function to produce a high-order detonation when all items are at or near liquid nitrogen temperature. Results obtained in this work showed that at least one brand of Number 8 commercial blasting cap was ineffective in initiating any of the explosives studied. If this result holds for all commercially available detonator/explosive combinations, it could be an important result.

EXPLOSIVES STUDIED

A total of 11 explosive formulations were studied. They are listed below:

Military dynamite, medium velocity, M2

Composition C-4

Du Pont Special Gelatin, 60 percent strength

Du Pont Gelex, Grade 1, 60 percent strength

Trojan Nitrostarch 60 WR, 60 percent strength

Red Dot smokeless powder

3FA black powder, Imperial Chemical Industries, Ltd.

Ammonium nitrate/fuel oil, 100 grams per 6-15 milliliters

Potassium nitrate/sulphur/charcoal, 75/15/10 by weight

Potassium chlorate/vaseline, 90/10 by weight

Potassium chlorate/powdered sugar, 55/45 by weight

Of the above formulations, all but the last four were used as received from the supplier. In the following paragraphs the preparation of the last four formulations is described in detail.

Ammonium Nitrate/Fuel Oil. This formulation was prepared from commercial fertilizer grade ammonium nitrate prills and Number 1 fuel oil. The two components were simply mixed together prior to loading into the charges. It was noted that there was some tendency for the fuel oil addition to run off of the ammonium nitrate prills and leak out of the charge. Hence, it cannot be expected that this mixture will be maintained in the test charges with any degree of precision.

Potassium Nitrate/Sulphur/Charcoal. This is the old standby, homemade black powder composition. For these tests the components used were reagent grade laboratory chemicals of high purity and finely powdered. The mixture was prepared by thorough blending of the weighed component powders.

Potassium Chlorate/Vaseline. This mixture was prepared from reagent-grade potassium chlorate and the standard commercial product by thorough mixing until the Vaseline was uniformly distributed throughout the mixture.

Potassium Chlorate/Powdered Sugar. This formulation was prepared by thorough mixing of reagent grade potassium chlorate with the commonly available confectioner's powdered sugar. The component parts were weighed separately and thoroughly blended together.

EXPERIMENTAL PROCEDURE

Three basic tests were conducted at room temperature and liquid nitrogen temperature on the explosive formulations to which the tests were applicable. These tests were initiation and reaction velocity studies, NOL large scale gap tests, and critical diameter for sustained detonation. The procedures utilized for the initiation studies will be described in detail in the Results and Discussion Section. The reaction velocities were measured using a National Bureau of Mines-developed resistance probe technique. This technique together with the large scale gap test and critical diameter studies will be described in the following paragraphs.

Reaction Velocity Studies

The reaction rates of all the explosive formulations were studied using a form of resistance wire probe initially developed by U.S. Bureau of Mines personnel^{(1)*}. Briefly the probes consist of coaxial assemblies comprising high resistance central wires in small diameter tubes. The resistance wire used is 40 AWG "Moleculoy" wire

* References are listed on page 42 of this report.

** Registered trademark of Molecu-Wire Corp., Skokeyville, New Jersey.

with a resistance of 87.15 ohms/foot, skip wound with nylon for insulation. A straight section of the wire is assembled into a section of aluminum tubing (0.020 in. OD x 0.0015 in. wall). During assembly of the probes extreme care must be exercised to maintain the straightness of both the aluminum tubing and the central wire to avoid the development of premature electrical contacts along the length of the probe. The probes are finished to the desired length by crimping the tubing securely over the central wire at one end and soldering small lead wires to both the aluminum tubing and central wire at the other end. A drop of plastic cement prevented shorting where the wire emerges from the tube. The probe is installed into the charge with the crimped end nearest the initiator so that the pressure front associated with the reacting charge sequentially shorts the central resistance wire to the aluminum sheath. To ensure that the advancing pressure front would crush the aluminum sheath, the probe was always employed with some firm backing behind it. In the case of charges enclosed in a steel pipe the probe was installed adjacent to the inside pipe wall. When the probe was employed with uncased charges an 0.02-inch-thick steel backing plate was taped to the probe in contact with the outer surface of the charge.

Figure 1 shows a schematic diagram of the connections employed with the resistance probe. The probes are powered by a constant current supply to make the voltage drop across the probe linear with its resistance change. The voltage drop across the probe is monitored remotely using an oscilloscope. Calibration of location of the pressure front on the oscilloscope trace is accomplished by recording on the oscilloscope record the trace locations when a standard resistor and a short are

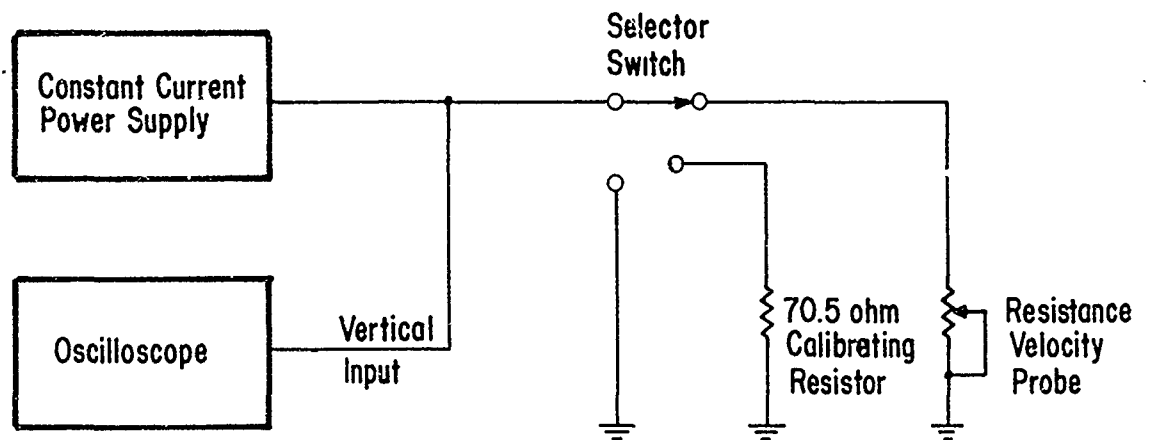


FIGURE 1. SCHEMATIC CIRCUIT DIAGRAM OF RESISTANCE PROBE CIRCUIT

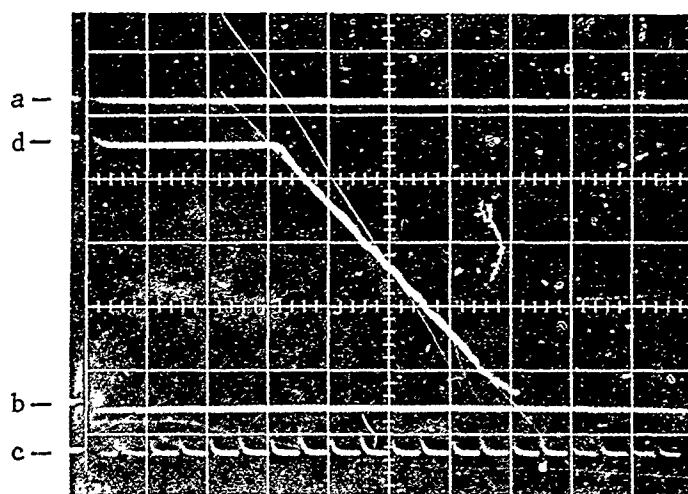
substituted in turn for the resistance probe, through use of the selector switch. The vertical calibration of the oscilloscope record is then simply found from the formula

$$\frac{\text{True location of reaction front (ft)}}{\text{Oscilloscope trace height}} = \frac{70.5}{87.15 h_c},$$

where h_c is the vertical distance between the trace locations when a 70.5 Ω standard resistor and a short are substituted for the probe. Calibration of the oscilloscope record is completed by either accurate adjustment of the oscilloscope sweep speed or recording a series of accurate timing marks on the oscilloscope record. For this work a Tektronix 502A oscilloscope was used. Sweep timing calibration was provided by a Tektronix Type 184 time mark generator which has a basic accuracy of at least 0.002 percent. The constant current supply was adjusted to provide an output current in the range of 30 to 60 milliamperes, to give a full screen deflection for the probe being used when the oscilloscope was set to approximately 1 volt per centimeter vertical sensitivity. Hence, typical voltage changes in operation of the probe were several volts, a value easily recordable, free of spurious noise.

A typical resistance probe record for a uniformly detonating explosive is shown in Figure 2. This record was obtained for composition C-4 detonating at liquid nitrogen temperature.

The measured reaction rates depend on the basic resistance per foot of the probe wire as part of its calibration. Thus a change in the wire resistance with temperature would affect the calibration. A separate check of the probe resistance from room temperature to liquid nitrogen temperature showed that the resistance remained constant to within < 1



Shot I-38

FIGURE 2. RESISTANCE PROBE RECORD FOR COMPOSITION C-4
 DETONATING AT LIQUID NITROGEN TEMPERATURE

Trace a was produced with the 70.5 ohm calibrating resistor replacing the probes. Trace b was produced with the probe shorted out. The vertical distance between traces a and b corresponds to $70.5 \times 12/87.15 = 9.70$ inches of probe length. Trace c was produced with the time-mark generator connected to the oscilloscope. The pulses shown are at accurate 5 microsec intervals. Trace d is the dynamic recording of the resistance probe functioning. The light scribed line on the photograph shows a slope equivalent to the detonation velocity of 28,200 ft/sec.

percent. Hence no change in the probe calibration is necessary for measurements made at liquid nitrogen temperature.

For the liquid nitrogen temperature shots, the explosive being tested, together with its assembled resistance probe and primer were immersed in liquid nitrogen for at least 1 hour prior to firing, (6 hours for the 4-1/2-inch diameter charge of ammonium nitrate/fuel oil). The shot and liquid nitrogen were contained in a disposable styrofoam

insulating container made by milling a cavity out of solid block foam material. The shots were fired while still immersed in liquid nitrogen, to avoid possible damage to the rather fragile probe assembly by rapid handling at liquid nitrogen temperature.

It is expected that the overall accuracy of the method is better than 5 percent when measurements are made of explosives which detonate at constant velocity. This accuracy is less than that of other methods but this approach has the advantage of providing a continuous record of the position of the pressure or shock front with time, together with ease of use and little requirement for a prior knowledge of the behavior of the explosive under test.

Large Scale Gap Tests

The NOL large scale gap test has been previously described⁽²⁾. The test, as originally formulated, used tetryl as the donor explosive, in the form of two pellets, each 2 inches in diameter by 1 inch thick, in contact with the "gap" material. The gap is formed of either solid 2-inch-diameter polymethylmethacrylate rod or cellulose acetate cards .01 inch thick, each or a combination of the two. Hence the sometimes name of "card gap test". The acceptor explosive under test is placed inside a 5.5-inch length of seamless steel pipe, 1.875 inches OD by 1.437 inches ID, in direct contact with the gap material. A 3/8-inch-thick square of mild steel is placed 1/16 inch off the far end of the acceptor charge as a witness plate. A detonation, or "go" is recorded for shots which punch a hole out of the witness plate. Other lesser forms of damage to the witness plate are recorded as "no-go". In successive shots the gap

length is varied until the "go" and "no-go" gap lengths are sufficiently close together. It is possible to continue the testing until the go and no-go gaps differ by only one card, in which case the test on both sides of the critical gap are replicated. However, for these scoping tests in which several explosives were tested at two temperatures, the testing for a particular condition was usually terminated with a somewhat wider spread between the maximum go and minimum no-go gap lengths.

The test results obtained in this study used pentolite donor explosive pellets in place of the original tetryl pellets. When NOS, Macon, Georgia, was closed a few years ago, there was no longer a satisfactory source of tetryl pellets, and a change was made to the use of pentolite pellets supplied by NAD Crane, Indiana. (Federal Stock No. 1375-991-8891.) The new pressure versus gap length calibration for pentolite donor explosive as given by Price⁽³⁾ was used in calculating the minimum no go and maximum go pressures shown in the tabulated results.

The gap tests run at room temperature followed standard procedures except that the tests were set up with the donor explosive up and the acceptor down. Tests run at NOL have verified that this configuration does not affect the results obtained. The witness plate was supported on low-density Styrofoam so that direct shock interactions between the witness plate and floor were avoided. This configuration proved convenient to use since only a short length of large-diameter (30-inch) scrap pipe was needed around the test to catch the high-velocity fragments generated by detonation of the acceptor charge.

In the gap tests run at liquid nitrogen temperature, only the acceptor charge in its containment pipe were cooled. The ends of the acceptor charge were closed using one layer of masking tape. This assembly was immersed in liquid nitrogen for a minimum of 1 hour. The charge was not completely temperature equilibrated in this time period but the temperature was undoubtedly near the desired temperature. After cooling, the acceptor charge was quickly transferred to the witness plate, the gap and donor placed on top and the shot fired. The time between removal of the acceptor from the liquid nitrogen and shot firing did not exceed 30 seconds.

Critical Diameter Tests

In these tests, charges of the various explosives were loaded into lengths of Pyrex glass tubing. Initiation was provided by 4 inches of cap-initiated, 100 gr/ft PETN Primacord for all explosives tested at room temperature. At liquid nitrogen temperature initiation was also by 4 inches of cap initiated 100 gr/ft Primacord for the military dynamite, C-4, and special gelatin. The Gelex and nitrostarch were initiated by a full-diameter, 1/2-inch length of C-4 initiated by Primacord. As in the detonation velocity studies, the detonating cap was maintained at room temperature with the temperature drop to liquid nitrogen temperature occurring along the Primacord.

Detonation or no detonation of the charges was determined by their effect on a witness plate placed in close proximity to the charge. To ensure that the detonation observed was steady, the charge length to diameter ratio was maintained near 5 or greater, and exceeded this value for most tests.

For all tests, the only confinement used was that of the Pyrex glass tubing, with wall thicknesses as noted in Table 2. The tests near liquid nitrogen temperature were conducted similarly to the gap tests. After soaking in liquid nitrogen, the preprimed shots were fired within 30 seconds after removal from the liquid nitrogen.

DETAILED RESULTS AND DISCUSSION

Detonating Explosives

At the beginning of this program very little quantitative data were available on the performance of the various improvised explosive mixtures to be studied. For this reason, and to establish baseline data for comparison, the room temperature and liquid nitrogen temperature performance of all the explosives or mixtures considered was studied initially, using various initiators and the resistance pressure probe as a means to determine reaction velocities. On the basis of these studies the explosives shown in Table 1 were found to detonate at relatively constant velocities. For these explosives, known to be cap sensitive, initial tests were conducted at room temperature and liquid nitrogen temperature using only a No. 8 commercial electric blasting cap or military blasting cap for initiation. These tests showed that none of this group of detonating explosives could be initiated by a cap only at liquid nitrogen temperature. In these tests, charge and detonator were both cooled together.

It was suspected that a possible reason for the failure to initiate at liquid nitrogen temperature was due to a reduction in the

TABLE 1. MEASURED DETONATION VELOCITIES

Explosive Type	Configuration	Room Temperature				Liquid Nitrogen Temperature				Remarks
		Initiator		Charge		Initiator		Charge		
		See Key Below	Propagation Velocity, ft/sec	Weight, g	Density, g/cc	See Key Below	Propagation Velocity, ft/sec	Weight, g	Density, g/cc	
Military Dynamite	Standard 1-1/4" x 8" stick	6	18,360	488	--	6	(a)	~188	(a)	
	Standard 1-1/4" x 8" stick					3		~188	(a)	
	In Pyrex tube, 1-1/32" x 10" long					7		165	(a)	
Composition C-4	1-1/2" x 10" in paper tube	1	26,200	439	1.52	1	(a)	439	1.52	Uniform detonations when obtained
	1-1/2" x 8" in paper tube					3		351	1.52	28,200
DuPont Special Gelatin, 60Z	In 1-5/8" x 12-1/2" capped pipe	2	19,300	689	1.62					
	Standard 1-1/4 x 8" stick	1	8,630	~240	--	1	(a)	~240	--	Uniform detonations when obtained
	Standard 1-1/4 x 8" stick	2	17,520	~240	--	3		~240	--	16,820
DuPont Cellex, Grade 1 60Z	In 1-5/8" x 10-1/2" pipe, no cap	2	15,230	447	1.25					
	Standard 1-1/2" x 8" stick	1	11,890	~290	--	1	(a)	~290	--	Room temp. detonations slightly irregular
	Standard 1-1/2" x 8" stick	2	11,370	~290	--	3	(a)	~240	--	(a)
DuPont Datasheet C 2 gm/in ² Sheet	Strip 2" x 12"	1	23,750	~48	--	1	(a)	~48	--	Thermal shock fractured Datasheet during cooling
Trojan Nitrostatarch 60WR, 60Z	Standard 1-1/4" x 8" stick	1	10,870	~180	--	1	(a)	~180	--	Room temp. detonation uniform
	Standard 1-1/4" x 8" stick					3		~180	--	(a)
Red Dot Smokeless Powder	1-5/8" x 12-9/16" capped pipe	2	11,950	237	0.555	2	11,340	243	0.555	Detonation vel. was ~1000 ft/sec faster over first 1/3 - 1/2 of charge than average values given
Ammonium Nitrate/Fuel Oil	In 1-5/8" x 12-13/16" capped pipe	4	Decaying (b)	433	--					
	In 4-1/2" x 9" x 1/8" wall Al pipe ends covered with 1/2" steel	5	(c)	~2200	--	5	--	~2200	--	(d)

Notes

1. 08 Cap only at indicated temperature.
 2. 08 Cap and 5/8" dia. x 1/2" thick Datasheet C booster at indicated temperature.
 3. 08 Cap initiating 100 gr/ft PETN Primacord at room temperature. Primacord was extended through temperature gradient to liquid N₂ temperature to initiate C-4 booster 5/8 in. in diameter by 1/2 in. long.
 4. 08 Cap initiating 100 gr/ft PETN Primacord at room temperature. Primacord was extended through temperature gradient to liquid N₂ temperature (if applicable) and to inside of pipe. C-4 booster inside pipe 1/2" long x full pipe diameter.
 5. Same as No. 4 above but C-4 booster 1" long.
 6. Military M6 special electric blasting cap only.
 7. Same as No. 3 above but C-4 booster 1" long.
- Notes
- (a) No detonation, much of charge recovered.
 - (b) Average velocity over first 4-1/2 inches, 660 ft/sec, approximately 1/2 of charge recovered.
 - (c) Velocity decaying slightly. Corrected (c) average over 4.0" beginning 1/2" from booster 7,660 ft/sec. Corrected average over last 3-1/2 inches, 6,820 ft/sec.
 - (d) Apparently only first half of charge reacted at an average corrected (c) velocity of 5,810 ft/sec.
 - (e) See Appendix for method of correction.

power of the detonating caps as a result of cooling. To test this hypothesis, both the No. 8 and military caps were fired near lead witness plates at both room temperature and liquid nitrogen temperature. In tests at both temperatures, the lead was maintained at room temperature to keep the response of the lead constant. The No. 8 cap at room temperature produced fragment craters from three well-defined layers of explosive mixture used in the cap. In the nitrogen temperature test the fragment craters from the middle layer were almost totally missing and the craters from the base charge were smaller and more conical in nature, showing a reduced fragment velocity. The military cap showed less well-defined layers but its output at nitrogen temperature was also very much reduced over its room temperature performance.

To develop a reliable source of initiation at nitrogen temperature, tests showed that 100 gr/ft PETN Primacord initiated at room temperature would carry the detonation down the temperature gradient to nitrogen temperature and initiate composition C-4 at nitrogen temperature. The C-4 showed essentially the same detonation velocity at liquid nitrogen temperature, and therefore nearly the same detonation parameters such as peak pressure generated. Thus, C-4 was expected to perform as a reliable booster for other explosives at liquid nitrogen temperature. This initiator is subsequently termed the gradient booster, and was used with slight variations for subsequent reaction rate studies and all critical diameter tests.

Table 2 presents the results of both the gap tests and the critical diameter studies for the detonating explosives. These results are based on a total of over 100 trials of the two testing techniques.

TABLE 2. GAP TEST AND CRITICAL DIAMETER TEST RESULTS

Explosive Type	Density Range gm/cc	Large Scale Gap Test										Critical Diameter (a) mm			
		Room Temperature				Liquid N ₂ Temperature				Pressure, kbar		Room Temp.		Lig. N ₂ Temp.	
		Gap, mm		Pressure, kbar		Gap, mm		Pressure, kbar		Max.	Min.	Max.	Min.	Max.	Min.
		Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.						
		Go	No Go	No Go	Go	Go	No Go	No Go	Go	No Go	Go	No Go	Go	No Go	Go
Military Dynamite	1.24-1.32	43.6	49.0	18.7	23.6	38.1	42.0	25.6	30.9	3.1	6.0	6.0	6.0	8.8	8.8
Composition C-4	1.58-1.61	51.1	52.1	16.7	17.3	38.4	45.6	21.5	30.5	3.9	6.0	6.0	6.0	6.0	6.0
Du Pont Special Gelatin, 60%	1.63-1.68	233.3	-	-	<5.3	65.5	98.9	5.4	10.6	8.8	10.2	30.9	33.8	33.8	17
Du Pont Gelex Grade 1, 60%	1.41-1.48	129.8	-	-	<5.3	51.0	64.7	10.9	17.4	3.9	6.0	41.4	45.9		
Trojan Nitrostarch 60 WR, 60%	1.17-1.21	61.3	65.3	10.6	12.0	53.4	64.5	11.0	15.9	11.5	14.4	33.8	41.4		
Red Dot Smokeless Powder	0.58-0.62	66.9	69.0	9.5	10.2	60.1	67.4	10.0	12.4	>38(b)	-	-	-	-	-

(a) Confined in Pyrex glass tubing with the following wall thicknesses:

<18-mm I.D. nominal 1-mm wall thickness
>28-mm I.D. nominal 2-3-mm wall thickness.

(b) Confined in 1/16-in. wall paper tube.

Based on the results of all these tests, the cap-sensitive detonating explosives studied can be divided into four groups. The military explosives, C-4 and military dynamite which are RDX-based explosives, comprise the first group. The nitroglycerin sensitized explosives, special gelatin and Gelex, comprise the second group. The nitrostarch explosive is placed in a fourth group. The effect of low temperatures on these groups of explosives are discussed in the following paragraphs.

The RDX-based explosives are both fairly insensitive to impact initiation at room temperature, as measured by the gap test. This property has been intentionally "built-in" to these military explosives through the use of desensitizing agents such as motor oil in their compositions. The desensitizer is thought to perform its function by coating the surfaces of the sensitive RDX grains making them less susceptible to hot-spot initiation at voids or other imperfections. Lowering the temperature could be expected to have relatively little effect on this desensitizing action. Indeed, the experimental data reveal relatively small further decreases in impact sensitivity of these explosives at liquid nitrogen temperature. Their high RDX content provides a rapid reaction rate, a short reaction zone-length, and consequently a reasonably small critical diameter at room temperature. For C-4, containing a higher percentage of RDX, neither the reaction-rate nor critical diameter for initiation is appreciably affected by changing to liquid nitrogen temperature. Military dynamite, containing less RDX, suffered a somewhat greater change in impact sensitivity and critical diameter than C-4, although the changes were still fairly small. The reaction rate of military dynamite at nitrogen temperature was not obtained although several

efforts were made to measure it. The military dynamite did not maintain a detonation when fired with a military cap or with the gradient booster in the standard paper covered sticks. In the critical diameter studies (not instrumented) a liquid nitrogen temperature detonation was obtained when the dynamite was enclosed in a glass tube of 8.8-mm diameter. It was suspected that the liquid nitrogen was penetrating the mass of explosive through its paper stick covering, thus preventing its detonation. Hence, an additional instrumented test at liquid nitrogen temperature was conducted using a sealed protective glass tube 26.2-mm I.D. and the gradient C-4 booster. This test also failed to sustain a detonation. It is expected, based on the performance of other explosives studied, that the liquid nitrogen temperature reaction rate is not far below that at room temperature.

The nitroglycerin-sensitized explosives both exhibited fairly high sensitivity to impact initiation at room temperature. Gap tests, with fairly long gaps were conducted at room temperature. These were extended to beyond the maximum gap length (100 mm) for which this test is calibrated in pressure, without obtaining a failure to detonate. The impact sensitivity of these explosives decreased appreciably at liquid nitrogen temperature. However they remained at least as sensitive at liquid nitrogen temperature as the room temperature sensitivity of nitro-starch and more sensitive than military dynamite at room temperature. Both of the latter explosives are readily initiated at room temperature by a No. 8 blasting cap without additional boosting. At room temperature, both the high and low detonation velocities characteristic of the special gelatin dynamite were obtained. The low velocity was established in a

single unconfined stick when initiated by an unboosted No. 8 cap. The high velocity was obtained when the charge was 1-5/8 inches in diameter confined in a pipe using the same initiator. At liquid nitrogen temperature, the characteristic high-detonation velocity was established in a standard stick under liquid nitrogen with the aid of the Primacord/C-4 gradient booster. The difference between the measured high-detonation velocities at room and liquid nitrogen temperature is within the experimental error of the measurements. No further efforts were made to determine the conditions for establishment of the low-detonation velocity in special gelatin at liquid nitrogen temperature.

The critical diameter for sustained detonation showed large increases for both of these nitroglycerin-sensitized dynamites at liquid nitrogen temperature. The special gelatin probably sustained a reaction in the standard stick size of 1-1/4 inches (31.8 mm) for the reaction rate measurements, even though the critical diameter test showed a failure at 30.9 mm diameter, due to the additional slight confinement provided by submersion in liquid nitrogen for the reaction rate test. The critical diameter for the Gelex dynamite was sufficiently greater than the standard stick diameter that detonation failed, even though it was submerged in liquid nitrogen. The coupled decrease in impact sensitivity and increase in critical diameter may be interpreted in terms of an increase in the reaction zone length of these explosives with decreasing temperature. If this is true, then similar effects of low temperatures in other nitroglycerin-sensitized explosives may be expected. It should be pointed out, however, that the nitroglycerin in these explosives was in the form of a gel rather than merely absorbed in a diluent as is the case

with straight dynamites. Although not studied in this program, the instability of at least some of the straight dynamites in the temperature range near the freezing point of nitroglycerin in the range near 0 C is known, and due precautions must be exercised in handling these compositions.

The nitrostarch explosive showed appreciably less room temperature impact sensitivity and a larger critical diameter than the nitroglycerin-sensitized explosives. The impact sensitivity at liquid nitrogen temperature showed a barely perceptible decrease from the room temperature value similar to the RDX-based explosives. The critical diameter for detonation however showed a large increase at liquid nitrogen temperature similar to the nitroglycerine-sensitized explosives. The divergent results of these two tests make the performance of nitrostarch somewhat puzzling.

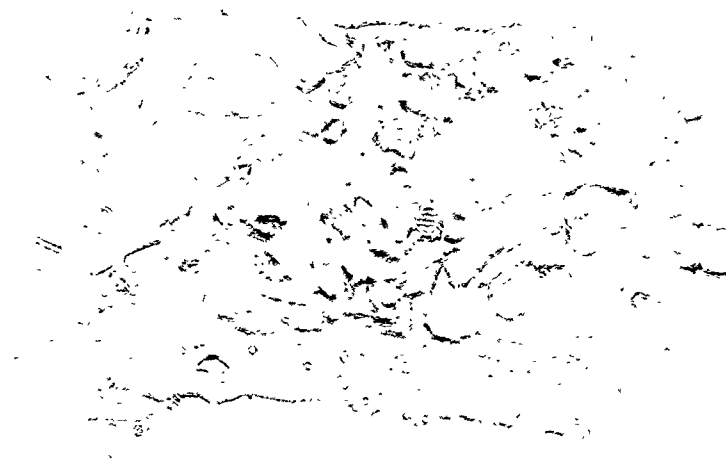
The remaining detonating explosives, Red-Dot smokeless powder and ammonium nitrate/fuel oil, are discussed separately in the following paragraphs.

A test of Red Dot smokeless powder at room temperature showed that confinement in a strong container such as a pipe was necessary to develop a high velocity reaction rate. A charge 1-1/2 inches in diameter confined only in a cardboard tube went out leaving most of the paper tube and unburned powder behind. The same cap plus detasheet booster applied to a charge confined in a 1-5/8-inch capped pipe reacted at an average rate of 11,950 ft/sec over 12-9/16 inches as shown in Table 1. The pipe fragments produced by this detonation are shown in Figure 3. Their appearance may be compared with a sample of the fragments produced by the detonation of a similar pipe configuration containing 60 percent

special gelatin as shown in Figure 4. The fragments from Red Dot are very similar. They show the highly stretched and torn shapes like those generated by detonation of the dynamite although the dynamite-generated fragments had a smaller average size. Fragments generated by both sources were very damaging although they were stopped by 1/2-inch thickness of steel.

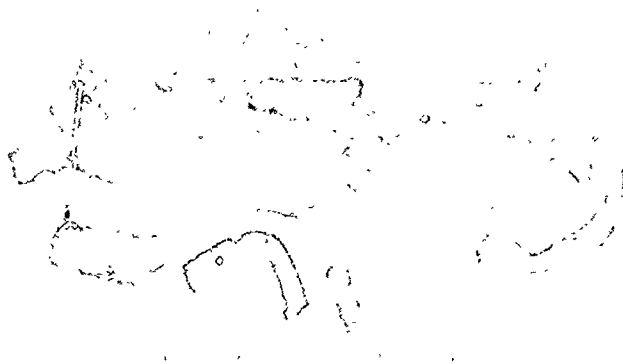
Figure 5 shows the appearance of the fragments produced by the detonation of Red Dot powder in a 1-5/8-inch-diameter capped pipe at liquid nitrogen temperature. Its average detonation velocity was 11,340 ft/sec over the length of the charge, which is within the experimental error of being the same as the room-temperature value. Note the greatly reduced average fragment size due to the brittle nature of the steel at liquid nitrogen temperature.

Red Dot smokeless powder responded as any other true detonating explosive when subjected to the NOL large-scale gap test. Its impact sensitivity was similar to that of the nitrostarch explosive and showed a barely discernible change at liquid nitrogen temperature as shown in Table 2. It should be noted that a fairly heavy-walled pipe confinement is present in the standard gap test configuration. Since the initial test of Red Dot in a 1-1/2-inch-diameter paper tube showed no tendency for propagation of a detonation wave in the absence of confinement, critical diameter tests on this material were not attempted, although in sufficiently large charges, with a sufficiently large booster, the self-confinement of the powder itself could produce a detonation. No data are currently available to indicate how large this charge size might be, other than that it is undoubtedly much greater than 1-1/2 inches in diameter.



Shot I-18

FIGURE 3. FRAGMENTS GENERATED BY CAP-AND-DETSHEET-INITIATED REACTION OF RED DOT SMOKELESS POWDER IN A PIPE AT ROOM TEMPERATURE



Shot I-1

FIGURE 4. FRAGMENTS GENERATED BY CAP INITIATED REACTION OF 60 PERCENT SPECIAL GELATIN IN A PIPE AT ROOM TEMPERATURE

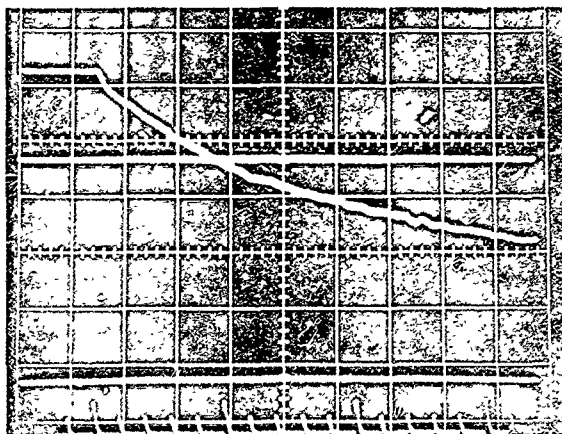


FIGURE 5. FRAGMENTS GENERATED BY CAP-AND-DETASHEET-INITIATED REACTION OF RED DOT SMOKELESS POWDER IN A PIPE AT LIQUID NITROGEN TEMPERATURE

The ammonium nitrate/fuel oil mixture (ANFO) is known to require relatively large charge diameters or heavy confinement. In commercial quarrying practice, it is not recommended for use in drilled holes less than 2 inches in diameter⁽⁴⁾, with larger diameters preferred.

Figure 6 shows the resistance probe record obtained when this mixture was fired in a 1-5/8-inches diameter capped pipe. The record shows a typical fading detonation characteristic of some explosives when initiated at less than their critical diameter. Note the slow progress of the pressure front. The average velocity over the first 4-1/2 inches of charge (~ 3 horizontal divisions in the figure after the start of reaction) was only 660 ft/sec.

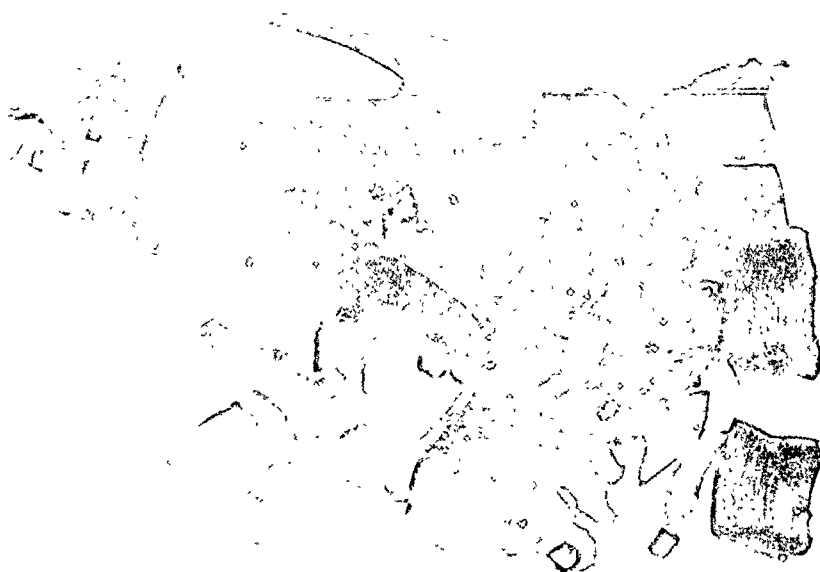
Figure 7 shows the appearance of the recovered pipe section after the shot recorded in Figure 6. Note the remaining unreacted mixture in the pipe.



Shot I-44

FIGURE 6. RESISTANCE PROBE RECORD FOR AMMONIUM NITRATE-FUEL OIL FIRED IN A 1-5/8-INCH DIAMETER CAPPED PIPE AT ROOM TEMPERATURE

The charge was initiated by primacord and 1/2-inch length of C-4 as a booster.



Shot I-44

FIGURE 7. APPEARANCE OF PIPE AFTER INITIATION OF AMMONIUM NITRATE-FUEL OIL AT ROOM TEMPERATURE

Note the remaining unreacted mixture in the pipe.

When the ANFO mixture was detonated in 4-1/2-inch-diameter steel or aluminum pipes at room temperature using a 1-inch-long, full-diameter booster of C-4, a continuing high-order detonation was obtained, although there was still evidence for a gradually slowing detonation velocity from the resistance probe record. The large ratio of charge diameter to length used in this shot makes a correction to the probe record for the effect of wave front curvature desirable. No truly accurate correction for this effect can be developed through analysis without the necessary data of the decay time/distance relation for the locally overdriven detonation wave in the ANFO near the booster charge. Based on the assumption of no overdriving and spherical spreading, constant velocity detonation waves in the ANFO, it is possible to develop a correction for the resistance probe record based on the geometry employed. This analysis is given in Appendix A. This correction represents the minimum necessary correction to be applied to the probe record to account for geometric effects alone. Decaying, overdriven detonation waves or detonation fading due to the charge diameter being less than the critical diameter for sustained detonation, will cause qualitatively the same deviations from a constant detonation velocity. Both effects would be apparent as a more or less gradual slowing of the observed detonation velocity. As noted in Table 1, this was the observed effect in the 4-1/2-inch-diameter charge, although the velocities measured were much higher and degree of slowing was much less than observed for the 1-5/8-inch-diameter charge. The present data are insufficient to determine which of the two possible effects were dominant in this case, although it is expected that the charge was probably less

than the critical diameter for the degree of confinement provided. This expectation is based on the relatively low observed detonation velocity over the final 4 inches of charge of only 6,820 ft/sec. This value may be compared with a sustained detonation velocity value near 11,600 ft/sec obtained by Cook⁽⁵⁾ for the same nominal ANFO composition in a paper tube just under 5 inches in diameter and over 36 inches long. The difference in the two detonation velocities observed was probably caused by Cook's use of a finely divided ammonium nitrate powder (although he does not specify this) where the present investigation used fairly coarse ammonium nitrate prills as shown in Figure 7. The effect of the use of coarse prills would be to increase the effective reaction zone length, thus decreasing the reaction velocity and increasing the critical diameter.

A 4-1/2-inch-diameter charge of ANFO was also fired with the same booster at liquid nitrogen temperature after soaking for 6 hours to equilibrate the temperature. In this case a slightly irregular but gradually decaying detonation velocity was observed over the first half of the 10-3/4-inch-long charge, followed by a cessation of probe closure. The corrected average velocity in this case was down to 5,810 ft/sec. Recovered fragments of the aluminum pipe suggested that the last half of the charge had not reacted although sufficient energy was released to preclude positive identification of any remaining unreacted mixture. This result shows that the low temperature caused a probable further increase in the critical diameter for detonation of this mixture, but did not completely prevent its rapid reaction and energy release.

Deflagrating Explosives

The four deflagrating mixtures studied consisted of two black-powder mixtures and two containing potassium chlorate. These mixtures are classified as deflagrating explosives because of the low propagation velocities measured and the large fragment sizes generated from the pipe bombs in which they were fired.

Table 3 shows the shots fired and results obtained for these mixtures. The detailed results obtained for each of the mixtures are described in the following paragraphs, in the same order as presented in Table 3.

Figures 8 and 9 show the appearance of the pipe fragments from 3FA commercial black powder at room temperature. The fragments shown in Figure 8 are the result of initiation by a Number 8 cap and Detasheet booster. The fragments shown in Figure 9 are the result of initiation by a squib.

Figures 10 and 11 shown the resistance probe records obtained for the two room-temperature initiation conditions of 3FA commercial black powder. The detonator-booster initiation of the charge produced an overdriven reaction velocity for the confinement provided by the pipe with the result that the reaction velocity was decaying over the charge length as shown in Figure 10. Note that two resistance probes were used in this shot. The results given in Table 3 are the average of the velocities measured from the two probes. The values obtained from the two probes were in agreement within experimental error for the values shown in Table 3. Near the end of the record one probe shorted out prematurely for a brief period.

TABLE 3. RESULTS FOR DETONATING MIXTURES

Shot	Explosive Type	Configuration	Explosive Weight, gms	Initiator See Key Bc. 0v	Temperature	Propagation Velocity, ft/sec	Comments Regarding Propagation Velocity Measurements		Pipe Damage Walls	
							End Caps			
7	3FA Black powder	In 1-5/8" x 12-1/2" capped pipe	432	2	Room	~840	Velocity obtained only for first 15 percent of charge	One intact	10 large pieces	
14		In 1-5/8" x 12-5/8" capped pipe	437	2	Room	~1110 ~675	Average first 6-1/2" slower	One in half	Similar to Shot 1-7	
27		In 1-5/8" x 12-13/16" capped pipe	435	8	Room	661	Average over entire length-irregular throughout	Both intact	One very large, four smaller pieces	
34		In 1-5/8" x 13" capped pipe	446	8	Liquid N ₂	(a)		Both broken ~20 pieces	Intact	
37		In 1-5/8" x 13" capped pipe	450	8	Liquid N ₂	~360	Average over entire length-closure occurred in Steps 3-4" in length	Both broken ~20 pieces	Intact	
17	KNO ₃ /sulfur/charcoal	In 1-5/8" x 12-9/16" capped pipe	495	2	Room		Charge went out, most recovered	End out of one	~3" of pipe split open	
32		In 1-5/8" x 12-13/16" capped pipe	~500	8	Room	(a)	Entire charge reacted	One intact	One large, ~11 smaller pieces	
33		In 1-5/8" x 12-13/16" capped pipe	~500	8	Liquid N ₂	(a)	Entire charge reacted	One in half	Fractured into ~10 ² pieces	
16	KClO ₃ /Vaseline	In 1-5/8" x 12-1/2" capped pipe	613	2	Room		Charge went out, most recovered	One broken	~3" of pipe split open	
19		In 1-5/8" x 12-3/4" capped pipe	653	9	Room		Charge went out, most recovered	One intact	~4" of pipe split open	
30		In 1" x 6-1/2" capped pipe	~123	8	Room	(b)	Squib fired but did initiate mixture	No damage-used same pipe for next shot		
31		In 1" x 6-1/2" capped pipe	~123	10	Room	(b)	Much unreacted mixture found	Both blown off	~3" of pipe split open	
20	KClO ₃ /powdered sugar	In 1-5/8" x 12-13/16" capped pipe	502	2	Room	730	Velocity irregular and obtained only for first half of charge	Ends out of both	~2" of pipe split open	
26		In 1-5/8" x 12-3/4" capped pipe	478	8	Room	(a)	Entire charge reacted	Both intact	One large, 7-8 smaller pieces	
43		In 1-5/8" x 12-3/4" capped pipe	490	8	Liquid N ₂	(c)	Entire charge reacted	Both broken ~20 pieces	Fractured into ~1-1/2 x 10 ² pieces	

Notes

(a) Reaction velocity not obtained due to scope triggering difficulties.

(b) Not instrumented for velocity determination.

(c) Pressure front not well enough defined to produce probe closure in organized way.

Initiators

2. No. 8 cap and 5/8" diameter x 1/2" thick Detasheet C booster.

8. Squib.

9. No. 8 cap and 5/8" diameter x 1/3" thick plus 1-9/16" diameter x 1/3" thick Detasheet C booster.

10. Cap initiated 30 gr/ft Primacord used as lead to pipe plus 2-3 turns coiled inside cap for booster.



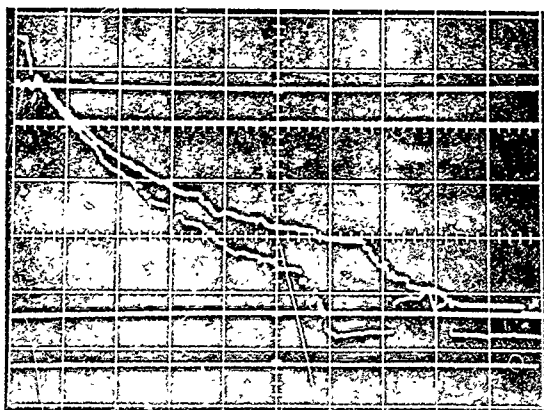
Shot I-7

FIGURE 8. FRAGMENTS GENERATED BY CAP-AND-DETSHEET-INITIATED REACTION OF 3FA COMMERCIAL BLACK POWDER IN A PIPE AT ROOM TEMPERATURE



Shot I-27

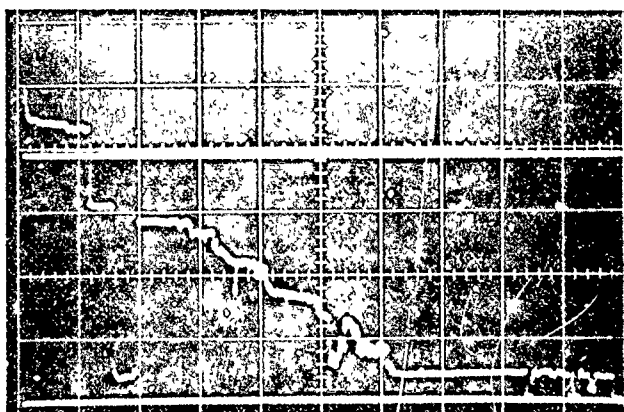
FIGURE 9. FRAGMENTS GENERATED BY SQUIB-INITIATED REACTION OF 3FA COMMERCIAL BLACK POWDER IN A PIPE AT ROOM TEMPERATURE



Shot I-14

FIGURE 10. RESISTANCE PROBE RECORD FOR THE CAP-AND-DETASHEET INITIATED REACTION OF 3FA COMMERCIAL BLACK POWDER IN A PIPE AT ROOM TEMPERATURE

The time scale is 200 microsec per major division (originally cm). In this record two probes were used, on opposite sides of the pipe. In the record, each probe has its own calibration and shorting trace. The value of the second calibration resistor was slightly higher (85 ohms) than the normally used 70.5-ohm calibrating resistor.



Shot I-27

FIGURE 11. RESISTANCE PROBE RECORD FOR THE SQUIB-INITIATED REACTION OF 3FA COMMERCIAL BLACK POWDER IN A PIPE AT ROOM TEMPERATURE

The time scale is 200 microsec per major discussion (originally cm).

Squib initiation of the 3FA commercial black powder charge produced the probe record shown in Figure 11. This record is typical of the resistance probe records obtained from the deflagrating mixtures. The reasons for the highly irregular nature of the record may be speculated to be associated with several factors. The reaction rate of the mixture is appreciably less than the sonic velocity along the pipe so that a pressure disturbance could be propagated along the pipe walls to the far end of the charge far ahead of the reaction front. At the far end of the charge, the probe passes through a small opening in the pipe cap where it might be particularly susceptible to a pressure disturbance of this sort. This could be the cause of the premature, momentary shorting of the active probe length before the reaction front had progressed down the charge. In some cases this effect frustrated efforts to measure reaction velocities by this technique*. Another factor probably associated with the production of somewhat irregular resistance probe records, aside from a truly irregular reaction rate, is that the progress of the reaction front is subsonic to the gas in the interstices. Thus the pressure front associated with the advancing reaction front is not a shock wave but rather a more gradually increasing pressure front. The functioning of the resistance probe used in these studies depends on the application of pressure to collapse the outer tube to affect a contact with the central high-resistance wire. This process could be expected to be somewhat irregular under the influence of a gradually increasing pressure front.

* The premature shorting of resistance probes due to this cause was minimized by using a larger clearance hole through the pipe cap and protecting the probe tubing by a short length of plastic "spaghetti" insulating tubing.

Figure 12 shows the appearance of the pipe and end cap fragments after the reaction of a charge of 3FA commercial black powder in a pipe at liquid nitrogen temperature. The charge was squib initiated. This unusual result was duplicated almost exactly in two shots. As noted in Table 3, the resistance probe record showed a series of sudden closures of 3 - 4 inches of probe length each. This "stairstep" record yielded an average velocity of 360 ft/sec. This figure is necessarily very approximate but is indicative of a considerably reduced reaction velocity at liquid nitrogen temperature of this mixture.

Figure 13 shows the fragments generated by the reaction of the homemade black powder mixture at liquid nitrogen temperature. Note that in this case the pipe walls were fractured into many pieces while one end cap remained intact and the other was simply broken in half. The nominal compositions of the homemade black powder and commercial black powder were very similar. Hence the principal factors responsible for this difference in behavior were probably the degree of pulverization and intimacy of mixing of the constituents.

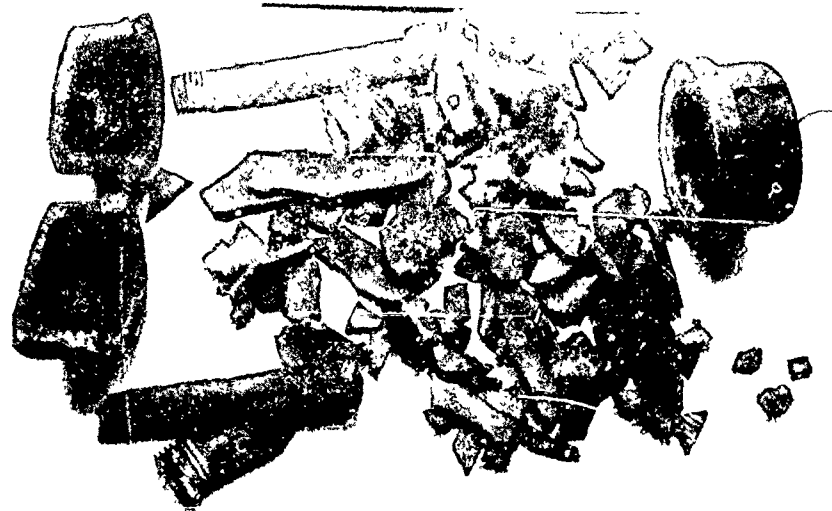
Figures 14 and 15 show the results of reaction of homemade black powder in a pipe at room temperature. The charge in Figure 14 was initiated by a cap and Detasheet booster. Very minimal reaction of the charge occurred. Note that the remaining black powder charge is still visible inside the pipe. The charge in Figure 15 was squib initiated. The results shown in Figures 14 and 15 for homemade black powder may be compared with those of Figures 8 and 9 for 3FA commercial black powder. It will be noted that although the reaction of the two mixtures to a detonator-booster was very different, their reaction to squib initiation at room temperature was



Shot I-34

FIGURE 12. APPEARANCE OF PIPE AFTER SQUIB-INITIATED REACTION OF 3FA COMMERCIAL BLACK POWDER AT LIQUID NITROGEN TEMPERATURE

There was no visible damage to the pipe of any kind, although the end caps were broken into many pieces.



Shot I-33

FIGURE 13. FRAGMENTS GENERATED BY THE SQUIB-INITIATED REACTION OF HOMEMADE BLACK POWDER IN A PIPE AT LIQUID NITROGEN TEMPERATURE



Shot I-17

FIGURE 14. APPEARANCE OF PIPE CONTAINING HOMEMADE BLACK POWDER AFTER INITIATION BY CAP AND DETASHEET BOOSTER AT ROOM TEMPERATURE

Note the unreacted mixture remaining in the pipe.



Shot I-32

FIGURE 15. FRAGMENTS GENERATED BY THE SQUIB-INITIATED REACTION OF HOMEMADE BLACK POWDER IN A PIPE AT ROOM TEMPERATURE

almost identical. No definite theories capable of explaining the observed differences in behavior of these two mixtures are known.

As noted in Table 3, several attempts were made to initiate the potassium chlorate/Vaseline mixture. The first two attempts used Number 8 detonators and Detasheet boosters. In the second attempt, the Detasheet booster was increased appreciably.

Figure 16 shows the result of the initiation attempt using a larger than usual Detasheet booster. The end cap and some of the pipe nearest the booster was fractured into small pieces. This result may have been caused almost completely by the booster. It is difficult to determine if any appreciable reaction of the potassium chlorate/Vaseline mixture occurred at all.

In the remaining two shots with potassium chlorate/Vaseline, both a squib and coiled primacord were used in the attempt to initiate an energetic reaction in this mixture. Both of these efforts also failed to produce evidence of reaction, and further studies of this mixture were terminated.

Figure 17 shows the results obtained from cap and Detasheet initiation of the potassium chlorate/powdered sugar mixture in a pipe at room temperature. The appearance of the pipe was very similar to that of Figure 14 for the same initiator in homemade black powder. The reaction of the potassium chlorate/sugar mixture, however, was complete and energetic enough to blow the central portion of the far end cap out in exactly the same way as the one adjacent to the cap and booster, as shown in Figure 17. The resistance probe record showed a typically irregular reaction rate, averaging about 730 ft/sec over the first half of the charge.



Shot I-19

FIGURE 16. APPEARANCE OF PIPE AND FRAGMENTS GENERATED BY CAP-AND-DETSHEET-INITIATION OF A POTASSIUM CHLORATE/VASELINE MIXTURE AT ROOM TEMPERATURE

The Detasheet booster used in this shot was appreciably larger than the usual Detasheet booster.

Shot I-20

FIGURE 17. APPEARANCE OF PIPE AND FRAGMENTS GENERATED BY CAP-AND-DETSHEET-INITIATION OF A POTASSIUM CHLORATE/POWDERED SUGAR MIXTURE AT ROOM TEMPERATURE

At this point the probe shorted out preventing further measurement. This reaction rate is comparable with those obtained from 3FA black powder at room temperature (see Table 3), but the potassium chlorate/sugar mixture caused much less severe damage to the pipe. This result is surprising in view of the performance of this mixture when squib initiated.

Figure 18 shows the appearance of the fragments generated by reaction of potassium chlorate/sugar in a pipe at room temperature when squib initiated. Comparison of this result with Figures 16 and 9 for the squib-initiated black powder mixtures suggests that the potassium chlorate/sugar reaction is very similar to that of the black powders at room temperature.

Figure 19 shows the appearance of the fragments generated by reaction of potassium chlorate/sugar in a pipe at liquid nitrogen temperature when squib initiated. Comparison of this result with Figure 13 for the homemade black powder shows that the average fragment size produced by the potassium chlorate/sugar mixture is somewhat smaller on the average. The severely broken end caps produced by the potassium chlorate/sugar mixture also indicate a somewhat more powerful reaction for this mixture. It should be noted that the most probable reason for the much reduced fragment size produced by the reaction of these two mixtures at liquid nitrogen temperature is the brittleness of the pipe material induced by the low temperature. Thus, it should not be inferred that the reactions of these mixtures were more energetic at liquid nitrogen temperature than at room temperature. However, the larger number of fragments generated could cause some additional hazard in terms of increased probability of striking a bystander.



Shot I-26

FIGURE 18. FRAGMENTS GENERATED BY THE SQUIB-INITIATED REACTION OF POTASSIUM CHLORATE/POWDERED SUGAR IN A PIPE AT ROOM TEMPERATURE



Shot I-43

FIGURE 19. FRAGMENTS GENERATED BY THE REACTION OF SQUIB-INITIATED POTASSIUM CHLORATE/POWDERED SUGAR IN A PIPE AT LIQUID NITROGEN TEMPERATURE

No direct measurements of the fragment velocity produced by any of the explosives studied were made. The damage produced by their impact on the surrounding containment chambers, however, merits some discussion. The fragments produced by all of the detonating explosives as a group were greatly more damaging on impact with their surroundings than were those of the deflagrating mixtures. A 1/2-inch thickness of steel (at distances from 1 to 3 feet from the pipe bomb in the form of an open-ended pipe, ~ 4 feet in length) was found to be capable of stopping all the fragments generated by the detonating explosive mixtures. Fragment penetrations were generally less than half this wall thickness. Some of the larger fragment impacts did cause the formation of stress-wave induced spall fractures near the outer surface of the container wall, however. The most common appearance was that of "blisters" on the outside of the containment pipe. These were occasionally torn open exposing the interior spall-fractured surface but few if any secondary spall-produced fragments were generated. The combined effect of fragments and blast from the detonating mixtures did cause a gradual local bulging of the containment pipe, requiring its replacement occasionally.

In contrast, the impact of fragments produced by the pipe bombs containing deflagrating explosives produced few if any visible craters or dents on the interior of the containment pipe, whether the mixtures were at room or liquid nitrogen temperature. For the deflagrations at room temperature, some curling of the pipe wall fragments and deformation of the pipe caps were apparent results of impact damage to the fragments themselves. No similar evidence of impact damage to the fragments generated by liquid nitrogen deflagrations were apparent. The brittle

nature of the metal at liquid nitrogen temperature could mask some of these effects, however.

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APPENDIX

DERIVATION OF CORRECTION TO MEASURED DETONATION VELOCITY
FOR LARGE DIAMETER, POINT INITIATED CHARGES

APPENDIX

DERIVATION OF CORRECTION TO MEASURED DETONATION VELOCITY
FOR LARGE DIAMETER, POINT INITIATED CHARGES

The problem solved in this appendix is the determination of the relationship between the true detonation velocity D and the apparent detonation velocity D_a measured along the outside diameter of a cylindrical charge which is point initiated at the center of one end.

Figure A-1 shows the geometry considered and the coordinate system selected to describe it. The point of initiation is at the origin, point O on the figure. The detonation wave is assumed to spread spherically from the origin beginning at time $t = 0$. Thus the equation for the location of the detonation front is given by

$$x^2 + y^2 = (Dt)^2 \quad . \quad (A-1)$$

The detonation velocity measuring probe is located along the line,

$$y = a \quad , \quad (A-2)$$

at the outer surface of the charge. The apparent velocity is thus the velocity in the x direction of the point of intersection between the expanding detonation wave and the charge surface. The location of this point is given by substituting Equation A-2 into Equation A-1:

$$x^2 + a^2 = (Dt)^2 \quad . \quad (A-3)$$

The desired apparent velocity is obtained by differentiating Equation A-3 and solving for the derivative:

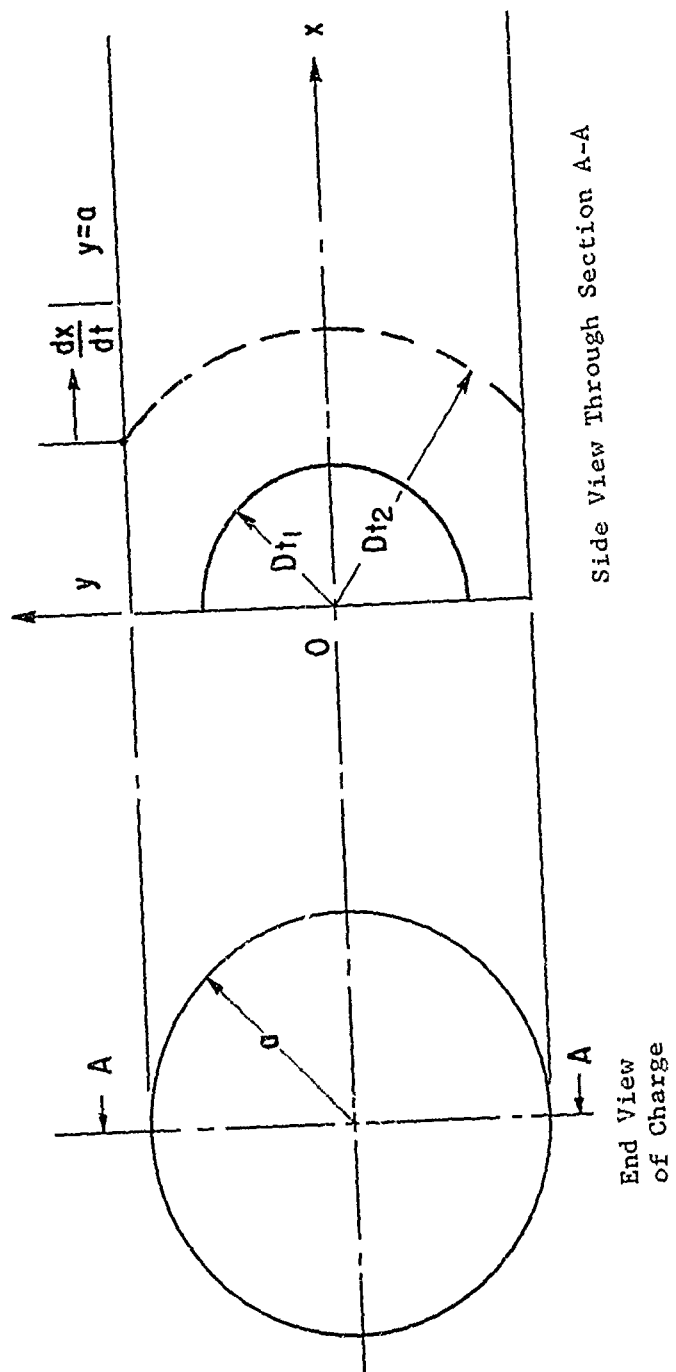


FIGURE A-1. CHARGE CONFIGURATION AND COORDINATE SYSTEM

$$D_a = \frac{dx}{dt} = D^2 t/x \quad . \quad (A-4)$$

This expression may be reduced to the following nondimensional form for plotting against the nondimensional coordinate x/a by simple algebra using Equation A-1:

$$\frac{D_a}{D} = ((x/a)^2 + 1)^{1/2} / (x/a) \quad . \quad (A-5)$$

For a more direct comparison with experimental data, the location of the detonation front at the measuring point expressed nondimensionally as a function of the dimensionless time Dt/a may be simply obtained from Equation A-3:

$$(x/a)^2 + 1 = (Dt/a)^2 \quad . \quad (A-6)$$

Figure A-2 shows plots of Equations (A-5) and (A-6). It may be seen that by the time the detonation wave has reached the surface of the charge 4 or 5 charge radii from the initiation end that the difference between the apparent and true detonation velocity is very small.

For the particular case of concern in the body of this report, i.e., a 4-1/2-inch charge diameter, the ratio of the apparent instantaneous detonation velocity to the true detonation velocity D_a/D is shown below for several distances x along the charge. Also shown for comparison are the dimensionless distance values x/a , and corresponding values of Dt .

<u>x</u> <u>inches</u>	<u>D_a/D</u>	<u>x/a</u>	<u>Dt</u> <u>inches</u>
0.25	9.06	0.111	
0.5	4.61	0.222	2.305
1.0	2.46	0.444	2.462
1.5	1.80	0.667	
2.0	1.505	0.889	3.010

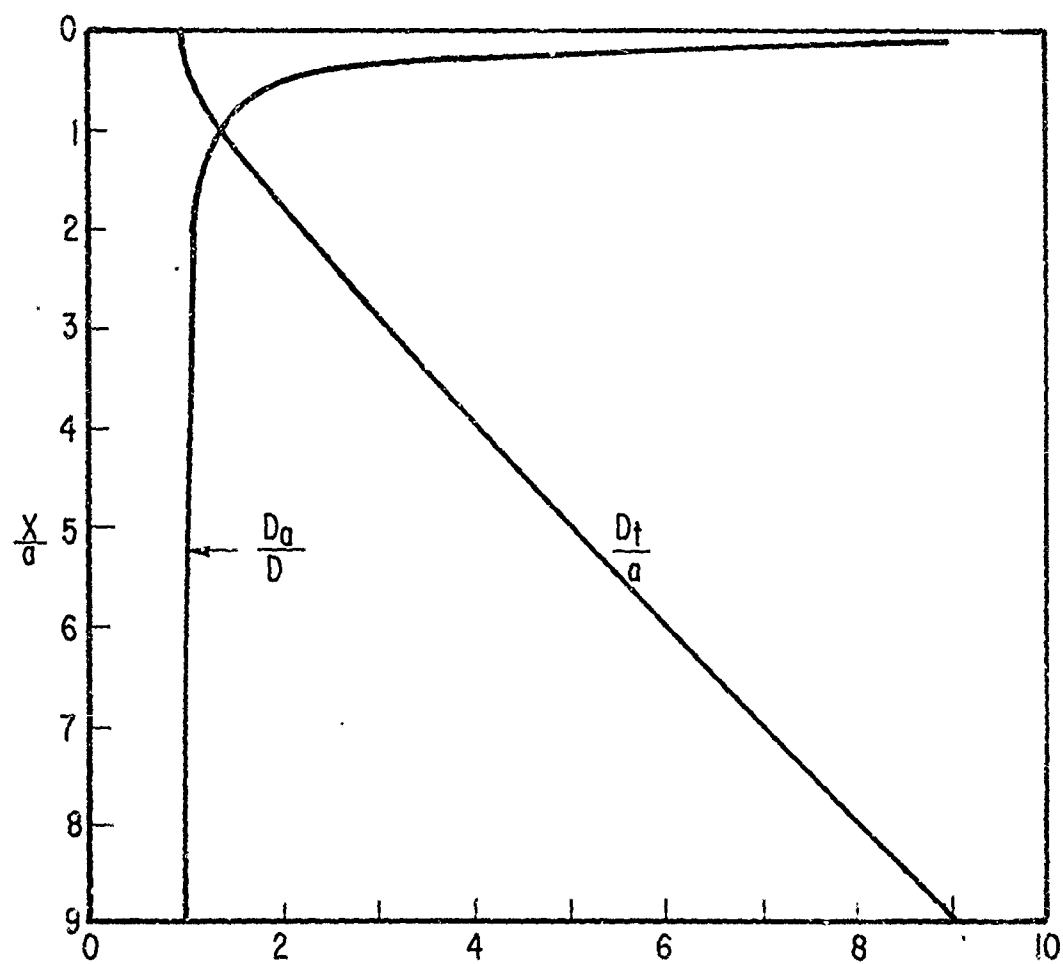


FIGURE A-2. DIMENSIONLESS PLOT OF DISTANCE VERSUS
DETONATION VELOCITY RATIO AND TIME

<u>x</u> <u>inches</u>	<u>D</u> <u>a/D</u>	<u>x/a</u>	<u>Dt</u> <u>inches</u>
3.0	.25	1.333	3.75
4.0	1.147	1.779	4.588
5.0	1.097	2.222	5.485
6.0	1.068	2.667	6.408
7.0	1.050	3.115	7.350
8.0	1.039	3.558	8.312
9.0	1.031	4.0	9.279
10.0	1.025	4.444	10.25

To make the corrections referred to in the text of this report a separate plot of Dt versus x was prepared using the above values. For the selected average velocities to be corrected, the average slope was measured over the same distances in this plot. The slope in this plot may be shown to be equal the correction factor D/D_a . Thus these slopes were used to correct the measured values.

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<p>The effect of liquid nitrogen temperature on the performance of eleven selected detonating and deflagrating compositions was studied experimentally. The detonating explosives included two military explosives, medium velocity dynamite and composition C-4, and five commercially available compositions. They included two 60-percent strength dynamites, 60-percent strength nitrostarch, ammonium nitrate/fuel oil, and Red Dot smokeless powder. The smokeless powder is included with the detonating compositions because true detonation waves were found to develop in pipe-confined charges of this powder. The deflagrating mixtures studied included both homemade and commercial black powder, and two potassium chlorate mixtures, one with powdered sugar and one with Vaseline.</p> <p>Measurements of the reaction velocity were made at both room and liquid nitrogen temperatures. Generally there was little change in reaction velocity between these two temperatures.</p> <p>For the detonating mixtures, the critical charge diameter for sustained detonation and the impact initiation sensitivity were determined at both room and liquid nitrogen temperatures. These tests for the deflagrating mixtures required confinement in pipe bombs.</p>			

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